Chapter 4
Modal Testing of a Composite Bladed Disc Using Travelling Wave Excitation Method

D. Di Maio, M. Vater, R. Seidel, and S. Foglia

Abstract This research article presents a novel application of travelling wave excitation method applied to a composite bladed disc. The objective of this work is to develop a non-contact excitation method for research applications where (i) blades are non-ferromagnetic and (ii) damping is nominally high. This goal was achieved by spinning a disc, on which 14 powerful DC magnets were installed, in front the composite bladed disc. Small DC magnets were attached near each blade root to provide repellent forces. Twenty blades were manufactured with pre-pregs IM7–8552, using unidirectional stacking sequence and were installed on a rigid metallic mounting hub. The paper will present the design and make of the bladed disc, the theoretical study of normal and tangential forces in a magnet-to-magnets configuration and, finally, the experimental validation of a 14-DC magnetic exciter. The forced responses were measured in one test case by a 3D single point LDV system and in another test case by a Scanning LDV system. This work will also present an attempt to develop a DC electromagnetic exciter with its limitation and potential.

4.1 Introduction

Vibration properties of bladed discs under stationary and rotating conditions have been studied for over several decades, during which numerous experimental methods were developed both for measuring and exciting blades. Literature highlights that one of the most challenging experimental goal is to excite and measure vibrations from blades with the smallest mass loading possible, the penalty being a corrupted dynamic behaviour of the system under study. All ferromagnetic materials can be easily excited by either an AC or DC source, which will work either under stationary or rotating conditions. Alternative experimental solutions can be found in literature when bladed discs are made of aluminium, which required some metallic/magnetic tabbing to attract/repel a magnetic excitation. Experimental works are furtherly complicated when dynamics are studied under rotating and vacuum conditions, whereby solutions for exciting non-ferromagnetic structures become very limited. Research on the bladed disc is, typically, focussed on the study of vibration properties under rotations to represent as much as possible operational conditions. However, any rotating object poses challenges on both excitation and measurement methods. Researchers studied excitation methods under stationary conditions to be able to replicate force patterns as similar to the ones experienced under rotation. This type of excitation has the form of travelling wave, which reproduces a loading pattern experienced by a bladed disc passing a fixed excitation source, such as a flow of combusted gases. The development of travelling wave excitation methods are reported in some papers [1–4]. The travelling excitation can be simply obtained by setting up some AC exciters in a circumferential direction up to a maximum number equal to the number of blades to excite. Each AC magnet will be then fed by a waveform differently phased from its neighbour. The phasing angle will depend on some parameters. This method was successfully to study mistuning of nodal diameters mode of vibrating bladed discs. Application of this experimental methods is seen in both magnetic and non-magnetic components. It was clear from the literature that all experimental works were limited to lightly damped bladed discs where the required excitation force was small. The difference between this research and the past literature is about the level of excitation force able to exert by using DC magnets set in rotations.

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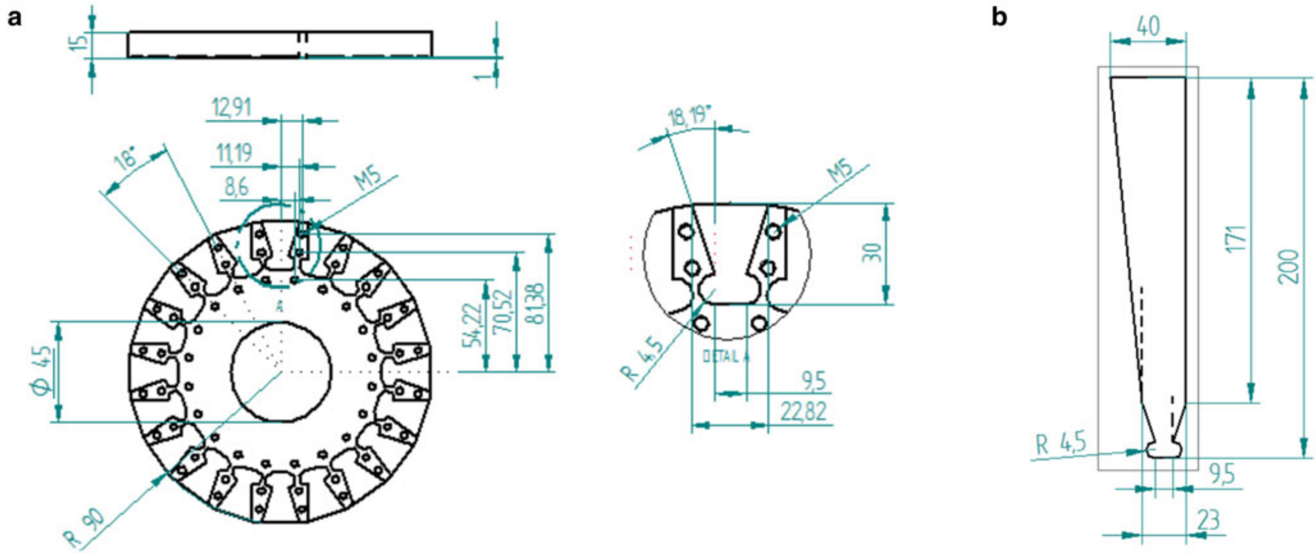

Fig. 4.1 Geometrical dimension of the mounting hub in (**a**) and blade in (**b**)

This research article is therefore focussed on the development of an excitation method for performing modal testing of a bladed disc made of non-ferromagnetic materials exhibiting considerable high damping. In fact, composite structures typically present higher damping than one made of mild steel and which can greatly affect the efficiency of the excitation method. In this research, the choice of composite materials was also due to the large expertise of the ACCIS group [5] in modelling and manufacturing thermosets composites, which are largely used in aerospace industry. One objective of this research is to develop a non-contact excitation method which is both able to (i) vibrate a bladed disc made of composites using travelling wave and (ii) to generate enough excitation force to achieve large vibration amplitudes. The paper will present various stages of this work. The first part will be focussed on the design & make of composite blades and mounting hub. Some experimental testing will be also presented. The second part will show the development of a novel DC electromagnet used to excite individual blades. Finally, the last part of the paper will focus on the theoretical study of force exchange between a magnet and a target, selected from metallic to magnetic. The study will then progress to the simulation of the magnitude and pattern of the exciting forces exchanged between a target magnet and the 14 magnets. The work will conclude by presenting the experimental validation of the 14-DC magnetic exciter used to excite the 20-bladed disc.

4.2 Design and Make of a 20-Bladed Disc

This section reports about the design and make of the composite blades and the mounting hub to hold the blades in position. The blade root was designed to have a dove tail geometry which matched the mounting hub profile. The blade root design was selected to avoid blade loss due to centrifugal load if the bladed disc were ever rotated. The mounting hub was made of two discs the inside part machined to accommodate the blade root. Figure 4.1a, b show the geometrical details of the mounting hub and the blade. The bladed disc was designed to install 20 blades made of carbon fibre composite material, IM7–8552. Each blade was made of 340 plies which were cut by a special cutter, using a segmented profile around the blade root as shown in Fig. 4.2a; this was necessary to avoid the tail to split during the cutting process. Figure 4.2b shows the pre-preg plies. Figure 4.2c shows the mould and the way it was made. The angle of rotation, 20 degrees, had to be as smooth as possible along the length of the mould and therefore several attempts were made to obtain an acceptable constant curvature. Figure 4.2d shows the final manufacture of the blade after the curing process. Instead, Fig. 4.3 shows the final assembly of the bladed disc.

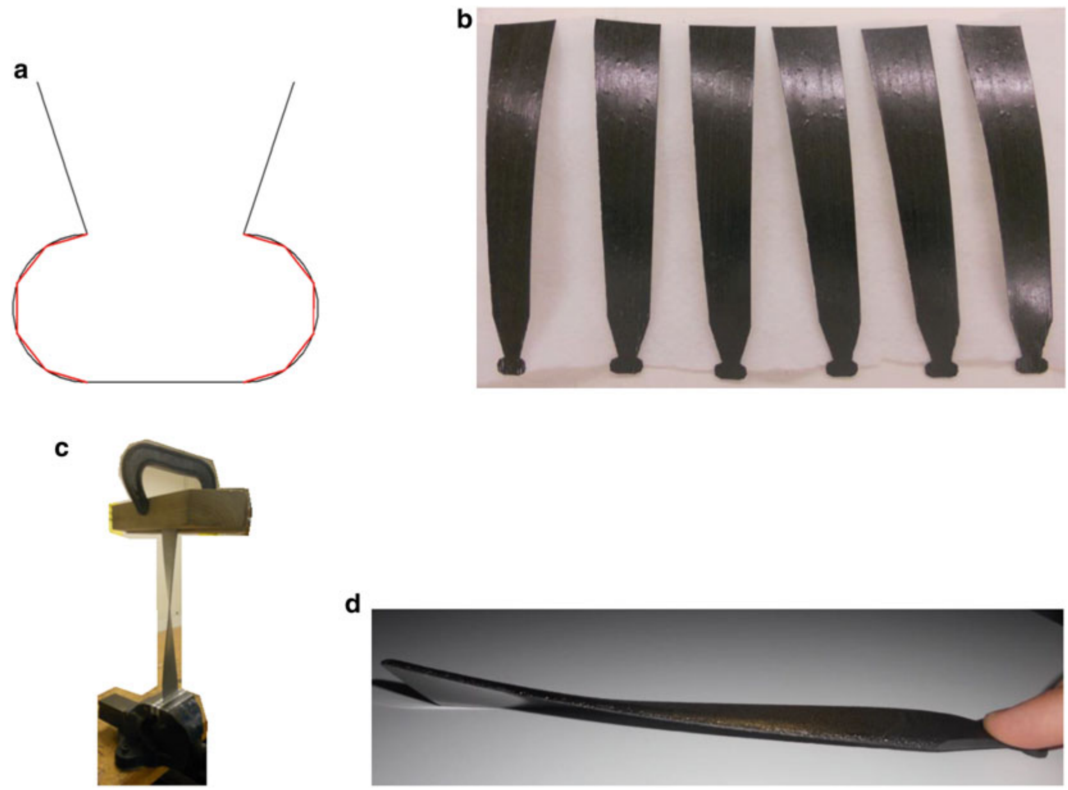

Fig. 4.2 Blade manufacturing steps. Blade root profile in (**a**). Unidirectional pre-pregs in (**b**). Tooling plate in (**c**). CRFP blade in (**d**)

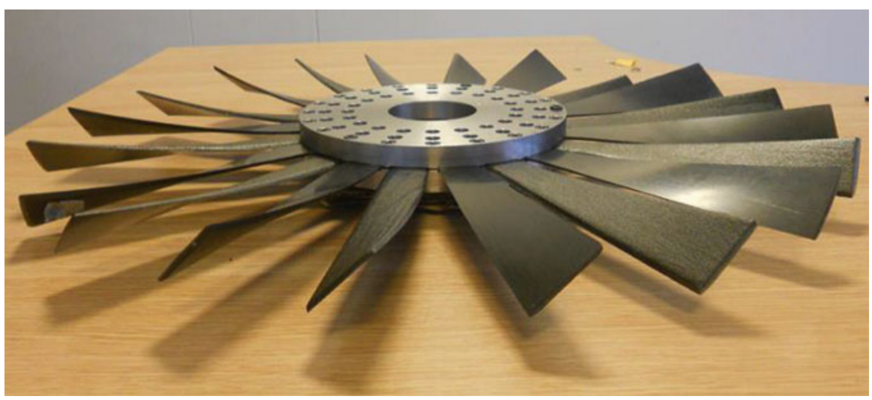

Fig. 4.3 Final bladed disc assembly

4.2.1 Vibration Testing by Modal Hammer and a Laser Vibrometer

After the assembly of the blades with the mounting hub, a vibration test was carried out by using a modal hammer and a 3D single point LDV. The bladed disc was installed in a rotating test rig, and reflective tape markers were stuck in each blade. Despite the silver colour sprayed on the dark blades, the laser reflectivity was not good enough. One of the major challenge was to measure all 20 blades without moving the laser head. This was achieved by fixing the laser head to a specific radial distance of the disc. All measurement points at that radial distance were rotated and positioned in front of the laser beam spot for carrying out the measurements, as showed in Fig. 4.4a, b. Then the laser head would be then moved to another radial distance, and the process would be repeated. The acquisitions were carried out by an LMS SCADAS system which measured the three outputs from the vibrometer, {X,Y,Z} vibrations, and the force of the impact hammer. Three averages per measurement point were selected. This type of measurement method proved to be very time consuming and therefore 4 points per blade were measured instead of the seven marked on each blade. Figure 4.4c–e show an example of FRFs

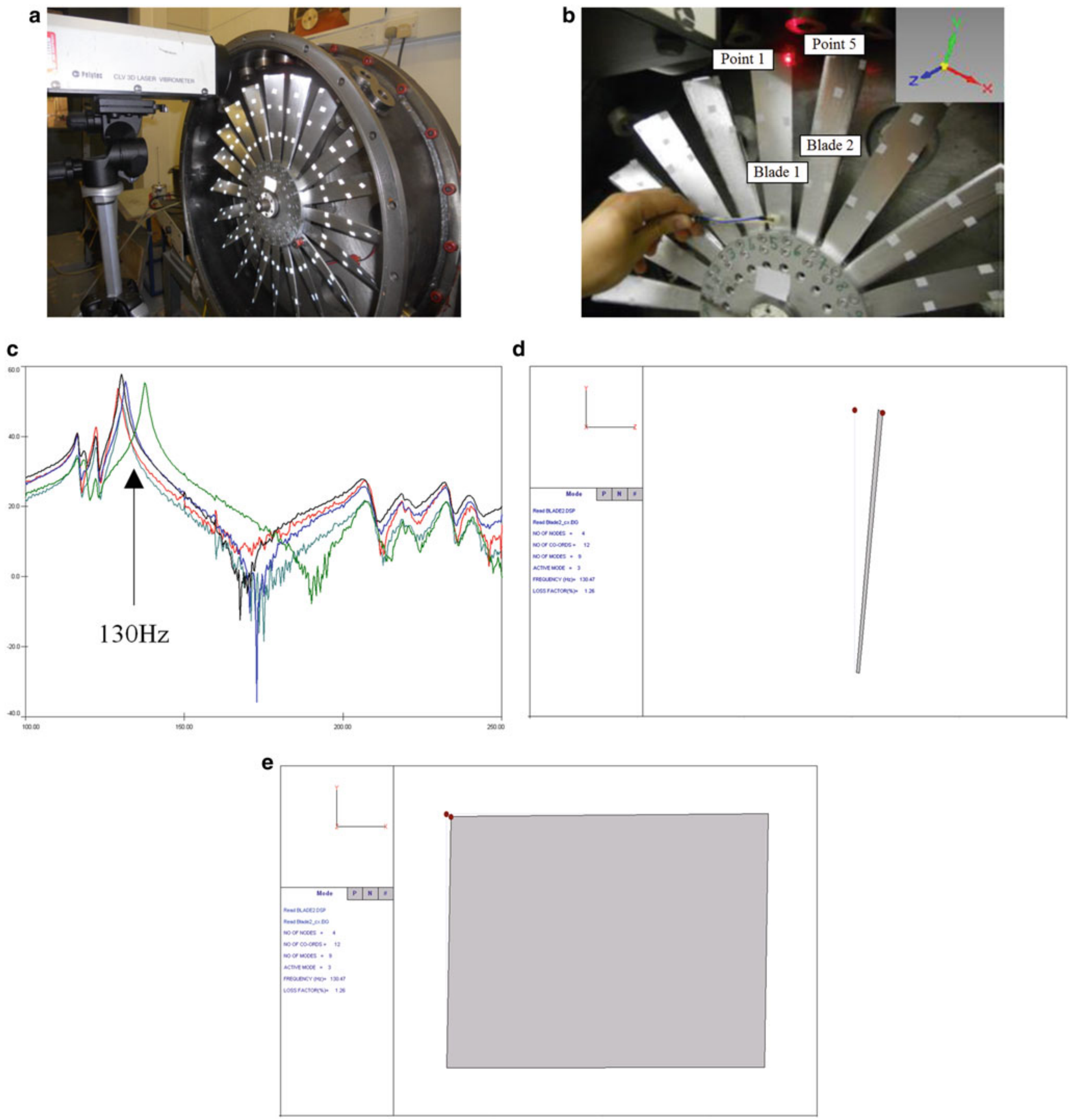

Fig. 4.4 Modal testing and analysis results. Test set-up in (**a**). Response and excitation location in (**b**). FRF in (**c**). Out-of-plane vibration in (**d**). In-plane vibration in (**e**)

(Z- out of plane direction), out of plane and in-plane mode of vibration, respectively. By carefully looking at Fig. 4.4c is possible to note that the out of plane mode presents a large frequency scatter (frequency at approx. 130 Hz) indicating a large mistuning response pattern. The mounting hub is very rigid with respect to the blade stiffness, and this shows as uncoupled disc and blade modes. Surprisingly, the in-plane motion of the blades seems to be more tuned, resonances of the blades show a qualitative smaller scatter. Finally, Fig. 4.4a shows that a force gauge was installed onto one blade in an attempt to use a shaker as excitation method. It was soon realised that the poor transmissibility between the blades did not make such an exciter very useful. Hence, it was decided to excite the blades individually.

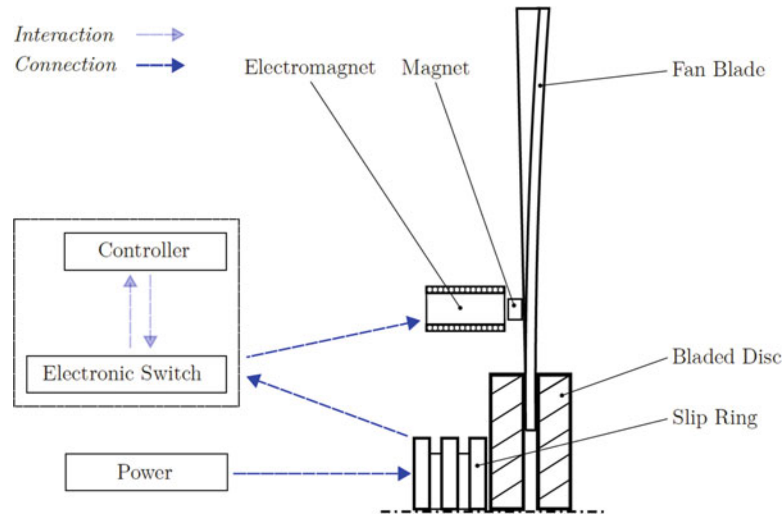

Fig. 4.5 Schematic of DC electromagnet exciter

4.3 Development of a Custom-Made DC Electromagnet Exciter

This section reports an attempt of developing a DC electromagnetic exciter. The initial idea was to develop an AC magnet rotating exciter [6] but, instead of one single magnet, there would be a magnet for each blade. Both the rotating exciter and the bladed disc would be locked on the same shaft, and the slip rings would feed the AC magnet. Unfortunately, the power requirement of 20 AC magnets would have caused issues with the slip rings power transmission. The idea was not abandoned, but a different approach was developed instead. A DC electromagnet was designed to create excitation force and, a simple schematic of the system is presented in Fig. 4.5. The basic idea is to feed an electronic circuit by a power generator. The controller and switch would create and deliver an intermittent power to the DC magnet placed right behind the blade to excite. A very small magnet is attached to the blade opposite to the DC exciter. The advantage is to feed much smaller power than the one required for AC magnets. Every blade would have its DC EM exciter with its own independent electronic circuitry. Ideally, the system could be set in rotation and the slip ring able to feed the electronic system using much smaller power than an AC system. Figure 4.6a shows the electronic system made of eight circuits able to control up to eight DC EM exciters, but only six of them were wired in. Figure 4.6b shows the electronic device installed on the rigid mounting hub, Fig. 4.6c the six DC EM exciters placed right behind the blades and Fig. 4.6d a schematic of the measurement setup controlled by a PC. An Arduino was used to control which of the exciter would be active.

The type of signal created by the electronics is an intermittent DC Voltage to the exciter, which is constantly switched on and off. A resonance frequency can be excited if pulsations is correctly built in a half period of oscillation as expressed by the following law $T_{0.5} = \frac{1}{2f}10^6 \mu sec$. Finally, Fig. 4.7a shows the frequency steps created for exciting any resonance in a frequency range between 130 and 180 Hz and in Fig. 4.7b the time series of the LDV output signal.

The idea behind this type of design proved to be correct and, in fact, a resonance on the blade can be excited. However, the excitation system was not developed further for several reasons; it was impractical to spin such an excitation system as designed. Nonetheless, a complete rethink of the system based on this proof of concept could be set in rotation. To conclude, this design can be also suitable for excitation of travelling wave under stationary conditions if the DC EM exciters are driven with an opportune phase shift. Despite this excitation method could set in resonance a blade it was not clear if a large vibration amplitude could be obtained and so it was decided to design something simpler and more performing.

4.4 Travelling Wave Excitation Method

Having showed in the previous sections how challenging could be the excitation of a bladed disc made of composite blades, this section will show an alternative solution which is focussed on DC permanent magnets.

The introduction and section 3 presented methods based on AC/DC EM magnets which are suitable for lightly damped structures. However, these methods become less efficient when damping is high. Another drawback is small vibration

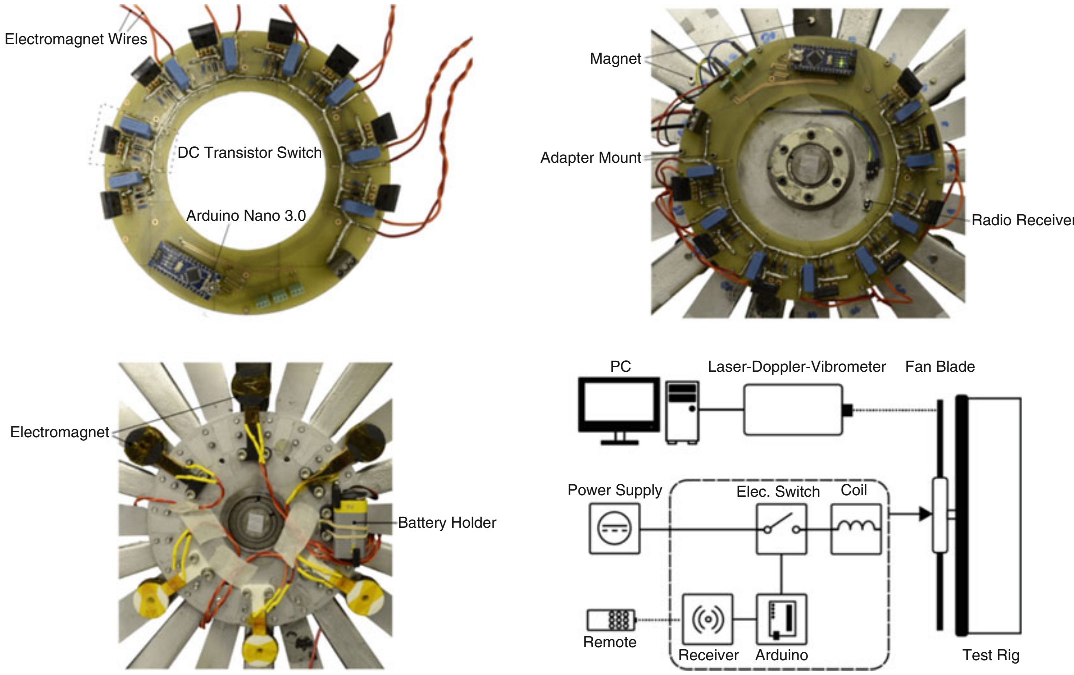

Fig. 4.6 DC EM exciters installed on the mounting hub and schematic of measurement setup

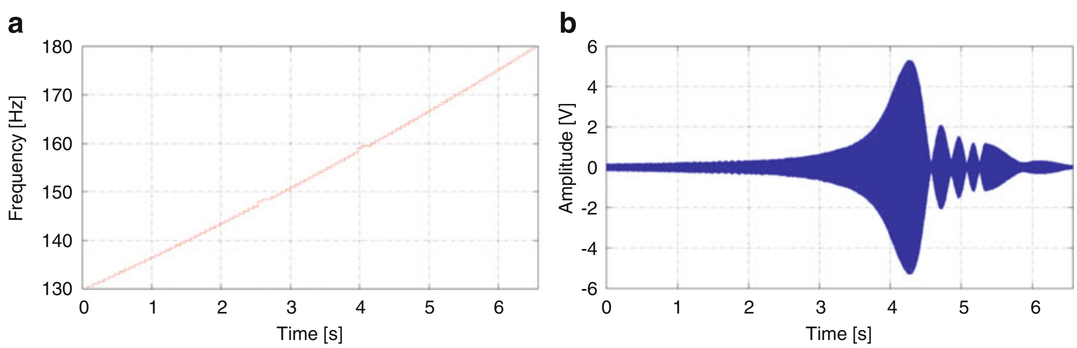

Fig. 4.7 Frequency steps in (**a**) and LDV output signal in (**b**)

amplitude achievable by these systems, which is not helpful when response amplitude dependent is studied. To overcome some limitations of the proposed exciters a different excitation method was developed. The objective was to reproduce (i) travelling excitation patterns and (ii) possible large response vibrations.

4.4.1 Modelling of Magnetic Force

Fourteen magnets (52 neodymium) were installed in an aluminium disc as showed in Fig. 4.8a. Such an excitation system would have worked with no problems with ferromagnetic materials, but composite bladed required an additional magnet to be attached to either repel or attract them. Figure 4.8b showed that the magnets were designed to repel thus avoiding any contact when the disc was spun. A Finite Element Magnetic Modelling was created to study some fundamental parameters such as the size of the magnet to install on the blade, the level of excitation force generated and the waveform pattern. For simplicity, a linearized model of the disc was created, and a target was moved incrementally alongside the set of 14 magnets, as showed in Fig. 4.9.

The density of the mesh was fine around the magnets to achieve adequate accuracy. The simulation work was divided into two parts, analysis to study the magnet-to-target and analysis to study the14 magnets-to-target. These are presented in the next section.

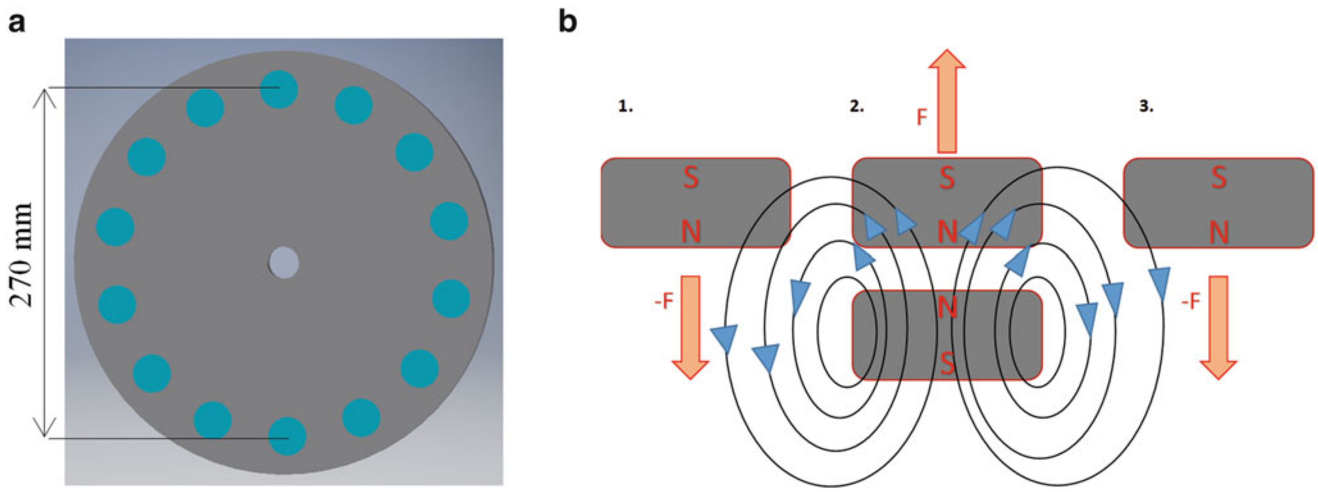

Fig. 4.8 Drawing of 14-DC magnet in disc in (**a**) and schematic of magnetic field in (**b**)

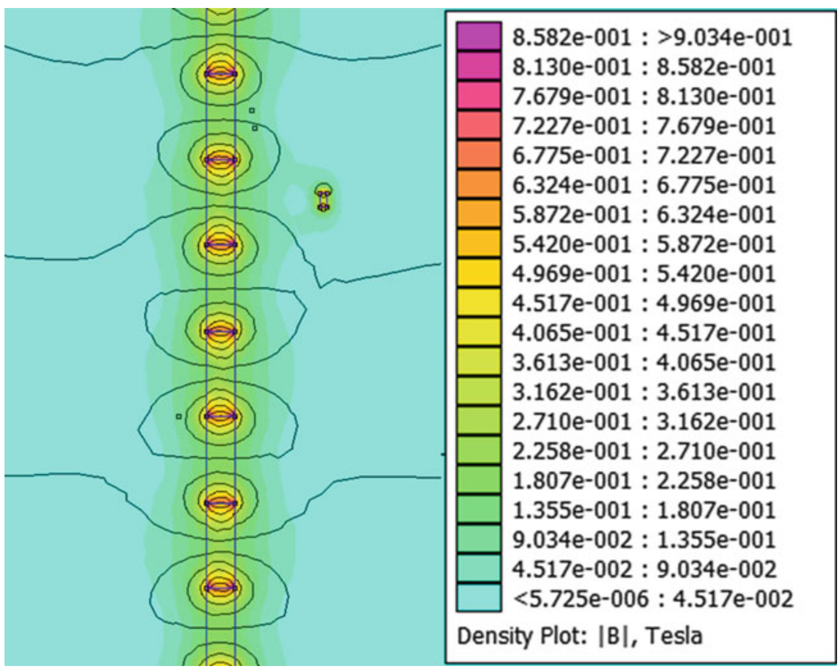

Fig. 4.9 FEMM model and magnetic force

4.4.2 Single Magnet Force Characterization

The first set of simulations were aimed to understand which type of targets could be selected for a composite blade. The requirement was to achieve a good sinusoidal waveform and a suitable excitation force. Table 4.1 shows the type of targets which were all, but one, magnets of different sizes. The targets were also studied according to the distance from the excitation source. The simulations were carried out by incrementally moving the target along Y-direction, see Fig. 4.10a. Normal and tangential forces were calculated and the angle between them. Every set of data was reported in a spreadsheet and plotted to evaluate force intensity with respect to their relative position and its shape.

Figure 4.10a shows the distance from the excitation source and the metal target where Fig. 4.10a–c show the force in X and Y direction and the angle between them, which allows calculating the resultant. The metal target presents an attractive X-force, negative sign, and a shear Y-force the magnitude of which are not high. Even the shape of the X-Force is not sinusoidal.

Table 4.1 Number of targets, material type and geometrical dimensions

Target	Material type	Dimensions
Magnet A	N52 Neodymium	Ø: 30mm h: 10mm
Magnet B	N52 Neodymium	Ø: 5mm h: 2.5mm
Magnet C	N52 Neodymium	Ø: 8mm h: 1mm
Metal	Mild steel	Ø: 30mm h: 10mm

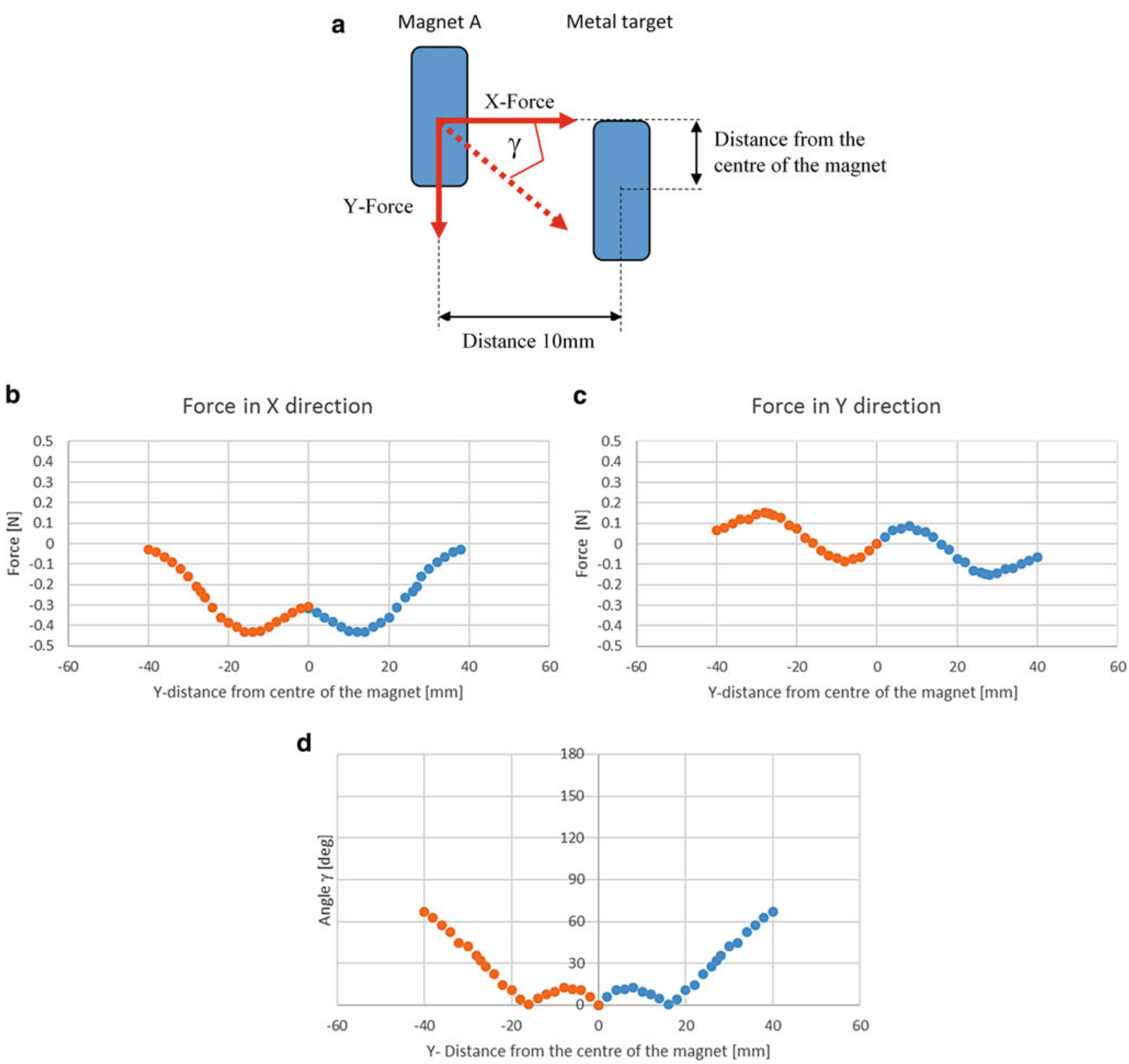

Fig. 4.10 Metal to magnet forces at 10 mm distance. Magnet-target configuration in (**a**). Normal force in (**b**). Tangential force in (**c**). Angle between normal and tangential force in (**d**)

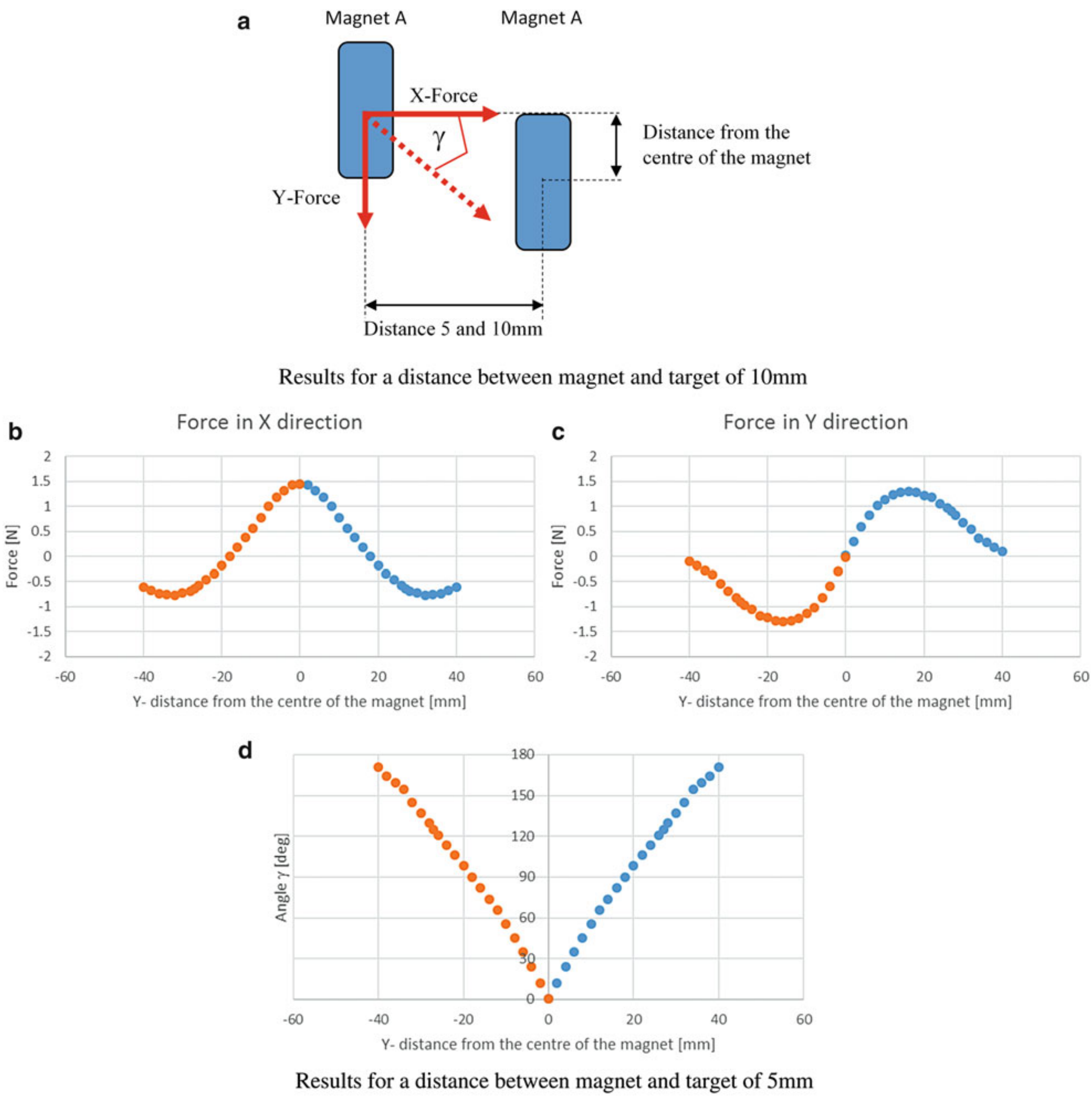

Fig. 4.11 Magnet to magnet (A-A) forces at 10 and 5 mm distance. Magnet-target configuration in (**a**). Normal force in (**b**). Tangential force in (**c**). Angle between normal and tangential force in (**d**)

Figure 4.11a shows the excitation and the target magnet of the same size, but two simulations were run for two different distances between them at 10 mm and 5 mm, respectively. Figure 4.11b–d show the forces and angle between them for a distance of 10 mm instead of the Fig. 4.11e–g show the same for a distance of 5 mm. It clear that the 10 mm distance produces a slightly better sinusoidal shape than the one for 5 mm.

Figure 4.12a–d show the results for two magnets of different dimension at a distance of 10 mm. Simulations for a distance of 30 mm were meaningless and therefore not reported. Figure 4.13a–d show results using two magnets of different size at a distance of 10 mm. Despite a similar shape of the X-forces, shown in Figs. 4.12b and 4.13b, their magnitudes seem to suggest that 5 × 2.5 mm size is better than the 8 × 1mm.

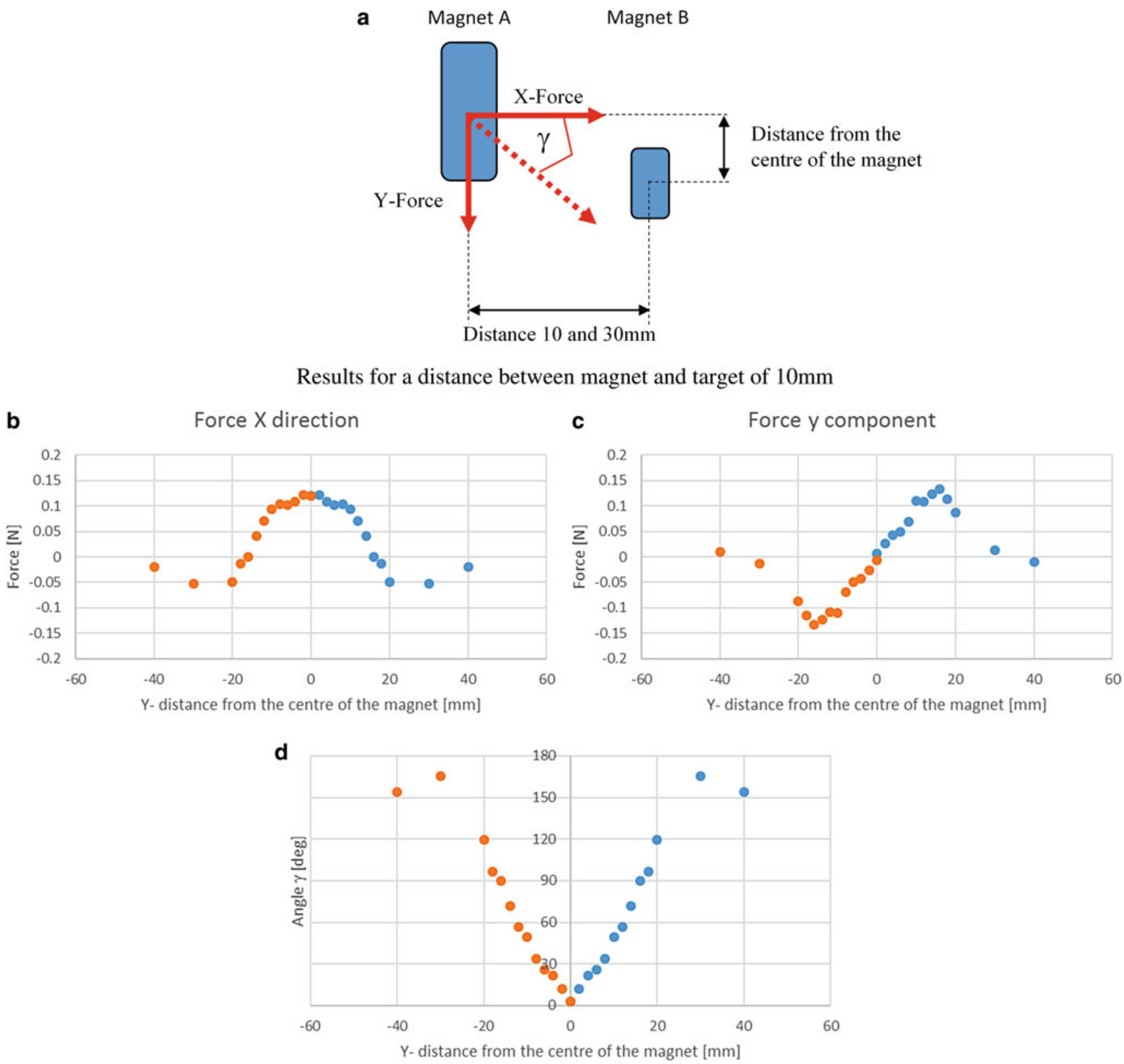

Fig. 4.12 Magnet to magnet A-B at 10 mm distance. Magnet-target configuration in (**a**). Normal force in (**b**). Tangential force in (**c**). Angle between normal and tangential force in (**d**)

4.4.3 Normal and Tangential Forces of Fourteen Magnets

The selection of the target was agreed on the 5 × 2.5 mm magnet since all other options were not practical for this application. Having said that, larger magnets could be used for the more specific type of tests where achievement of very large amplitudes is more important than other geometrical/dynamical parameters.

The 14 magnets, displaced in the circumferential direction, were modelled along a straight line but without altering their relative distances. Simulations were run by incrementally sliding the target magnet along the Y-direction as showed in Fig. 4.14a. Figure 4.14b–d show the X-Y forces and their relative angle. The simulations were not carried out for the full length of the original circumference ($c = \pi * 270\ mm = 848.23\ mm$) but a shorter distance such as 175 mm. The peak-peak amplitude obtained by using a 5 × 2.5 mm target is excellent and, also, the shape of the force which is quite sinusoidal. These results were very encouraging, but they required an experimental validation which is the focus of the next section.

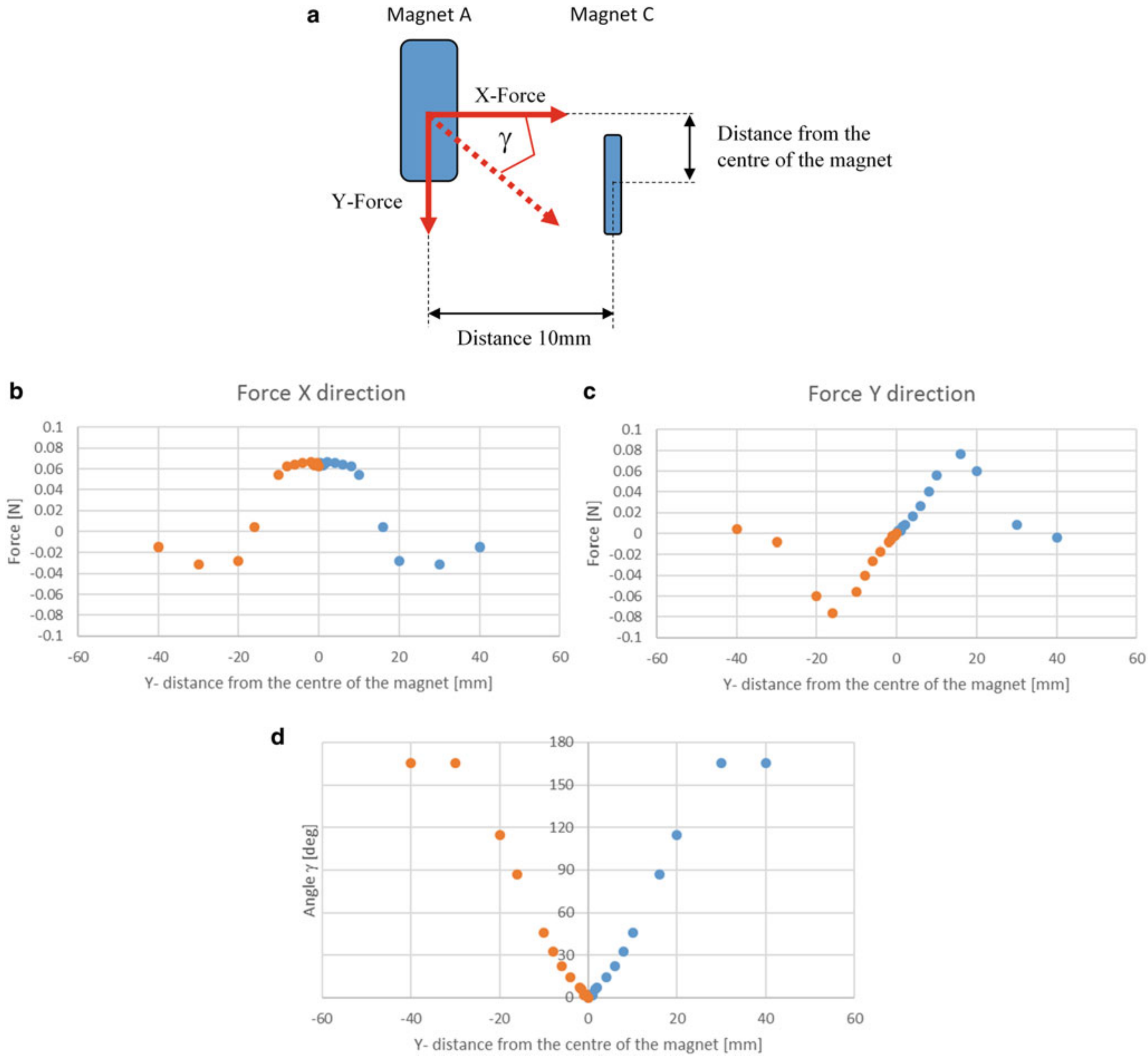

Fig. 4.13 Magnet to magnet A-C at 10 mm distance. Magnet-target configuration in (**a**). Normal force in (**b**). Tangential force in (**c**). Angle between normal and tangential force in (**d**)

4.5 Experimental Characterization

The theoretical results had to be verified against a set of experiments. These experiments were organized according the following requirements such as (i) fixed target Vs. spinning 14-DC magnet exciter, (ii) cantilever blade with 5 × 2.5 mm magnet Vs. spinning 14-DC magnet exciter and, finally, fixed 20 bladed disc Vs. spinning 14-DC magnet exciter. Figure 4.15a shows the spinning test rig used for the experiments, where Fig. 4.15b shows the force gauge on which the target magnet was installed. It is also possible to observe an accelerometer which was installed to monitor any vibration caused by the shear forces of the 14 magnets. However, no significant vibrations were recorded. The 14-DC magnet exciter was installed on the shaft and spun past the fixed target using five rotational speeds such as 200, 500, 800, 1100 and 1400 rev/min. The signal from the force gauge was measured by a DAQ NI card using 10,000 Sample/sec.

Figure 4.16a shows a portion of the time series measured by the force gauge at 500 rev/min. Figure 4.16b shows the spectrum of the whole signal where it is possible to appreciate the number of harmonics present, in particular, one at approx.

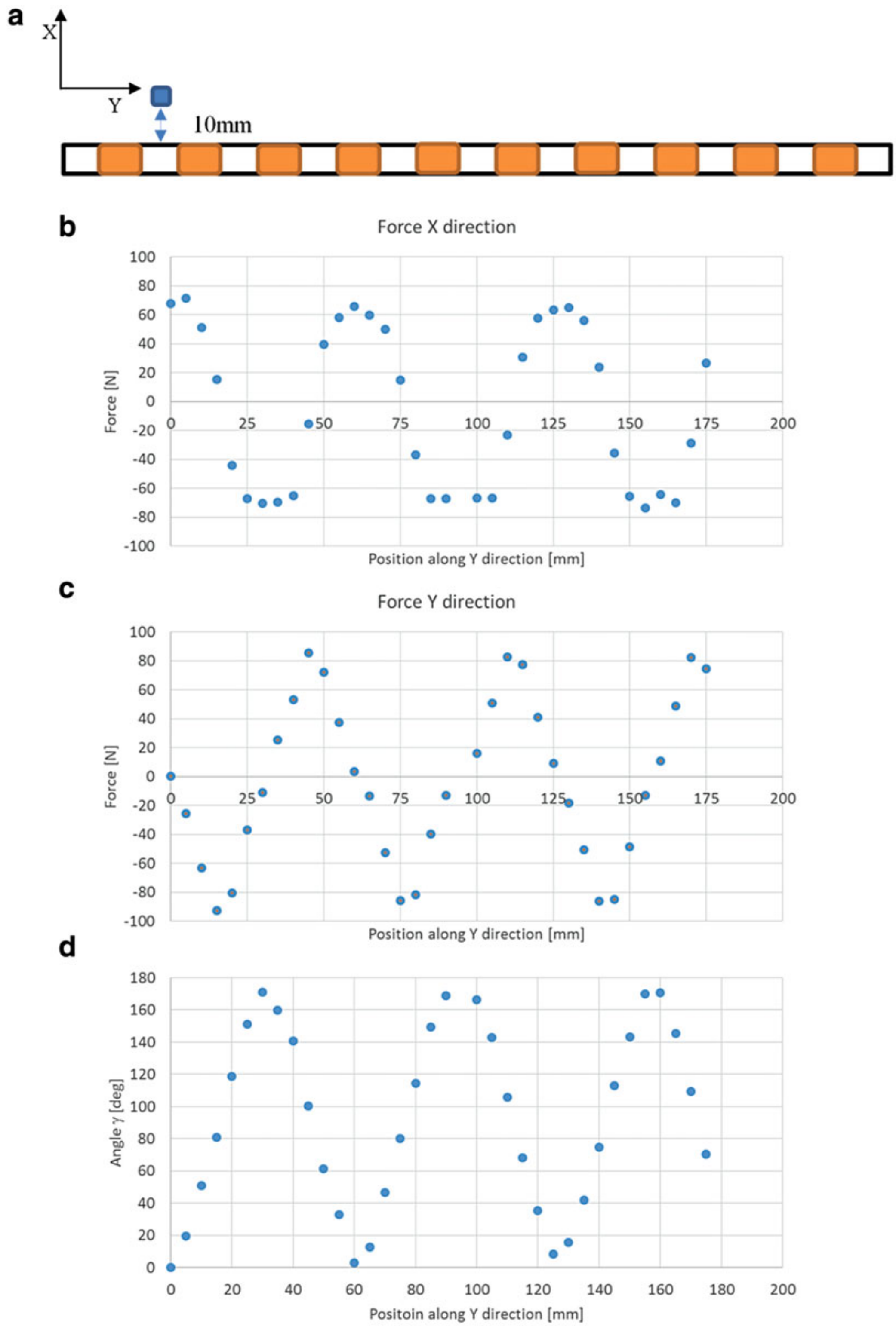

Fig. 4.14 Simulation of X-Y forces in 14-magnet configuration with 5 × 2.5 mm target magnet. Magnet-target configuration in (**a**). Normal force in (**b**). Tangential force in (**c**). Angle between normal and tangential force in (**d**)

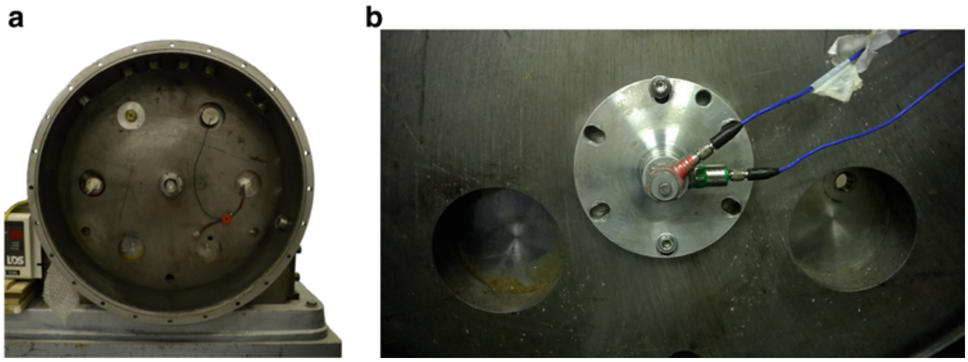

Fig. 4.15 Test chamber in (**a**). Target attached to force gauge in (**b**)

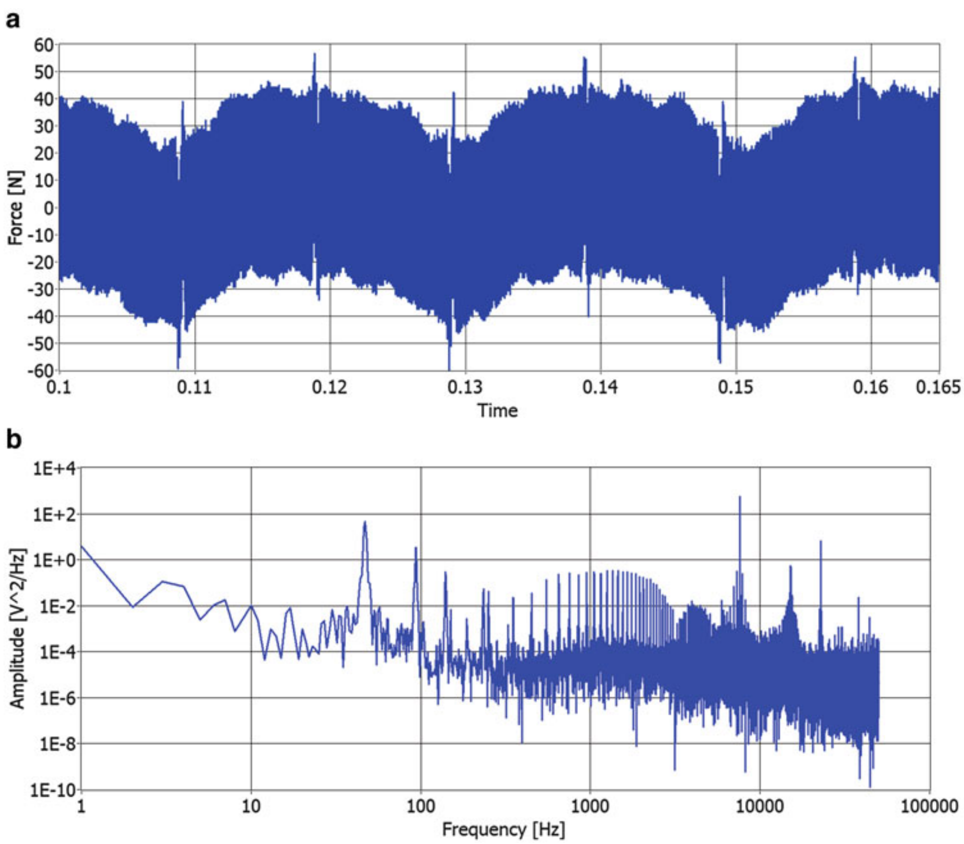

Fig. 4.16 Time series of the force measured by the gauge in (**a**) and its spectrum in (**b**)

7.586 kHz. Figure 4.17 shows a short portion of the time series in blue and the filtered signal in red. The filter was a passband Butterworth 1st order.

By filtering the 7.586 kHz oscillation it was possible to plot the underlining oscillation for different rotational speeds setup for the experiments. Figure 4.18a–d show the excitation force without all spurious harmonics and a dominant one at 7.586 kHz. The peak-peak excitation force is approx. 18 N in all the presented test cases, which show a remarkable sinusoidal waveform shape. However, the actual measured force is smaller than the simulated one. It is not clear why and what triggered the 7.586 kHz harmonic oscillation and if that frequency can be considered the peak-peak signal, which is approx. 90 N peak-peak but still lower that the one calculated (approx. 140 N).

The first set of experiments showed useful results both in terms of excitation force exerted and in terms of sinusoidal patterns at different speeds. The next phase was to use a cantilever composite blade with the same target magnet, 5 × 2.5 mm, and repeat the test by exciting the first bending mode of the blade. The target magnet was installed at the same location where it would be for the 20-bladed disc configuration. Figure 4.19 shows the forced response vibration of the composite

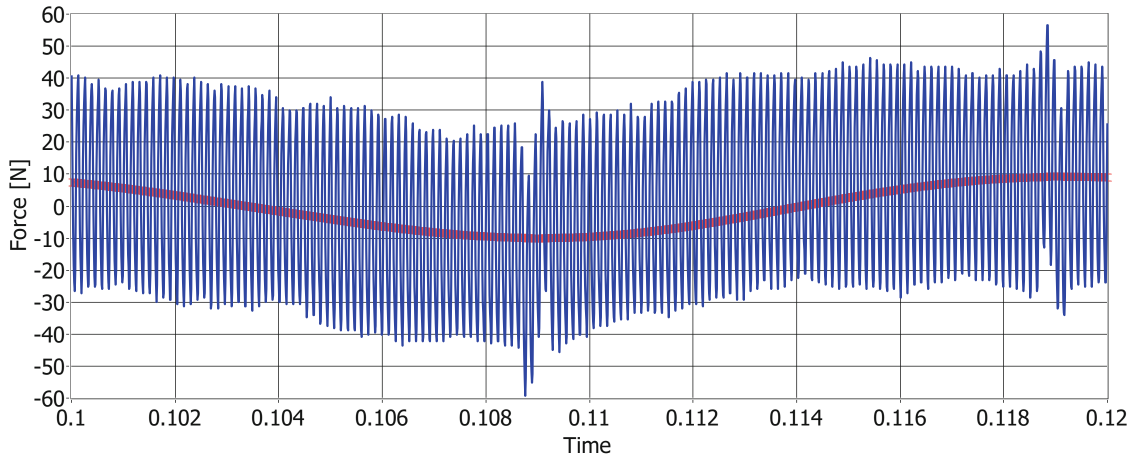

Fig. 4.17 Filtered (red) and unfiltered signals (blue) of the force gauge

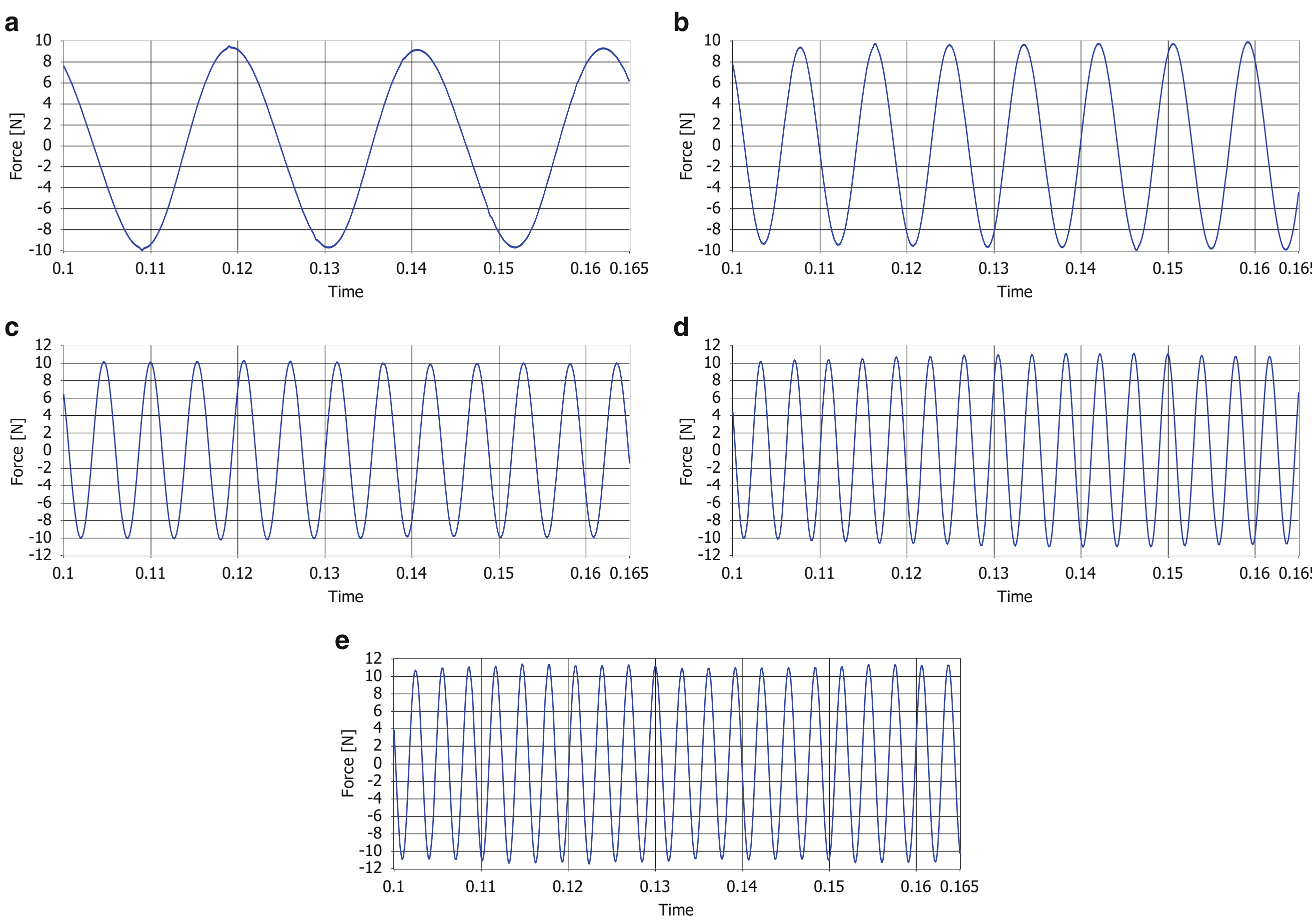

Fig. 4.18 Filtered waveforms measured at different rotational speeds, 200 rev/min in (**a**), 500 rev/min in (**b**), 800 rev/min in (**c**), 1100 rev/min in (**d**) and 1400 rev/min in (**e**)

blade, where it is a noticeable skewness caused by the large vibration amplitude generated by the exciter; a typical nonlinear behaviour. The final stage of the experiments was to rigidly fix the 20-bladed disc on the back plate of the test rig and have the 14-DC magnetic exciter spinning in front of it. One target magnet 5 × 2.5 mm was installed for each blade of the disc. Figure 4.20 shows both the bladed disc with the target magnets and the exciter installed in from of the bladed disc. A Scanning LDV system was used to measure the response from four measurement points marked by reflective tapes (mid measurement point

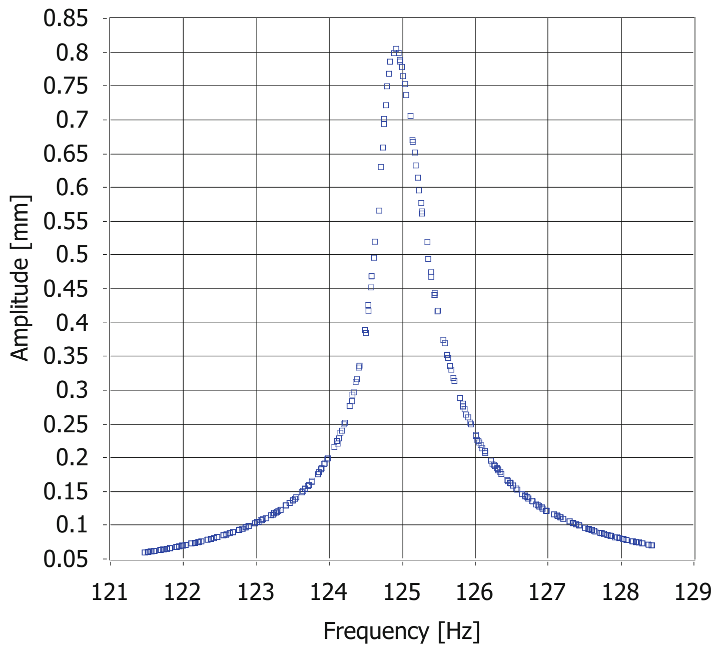

Fig. 4.19 Forced response vibration of a cantilever blade excited by the 14-DV magnet exciter

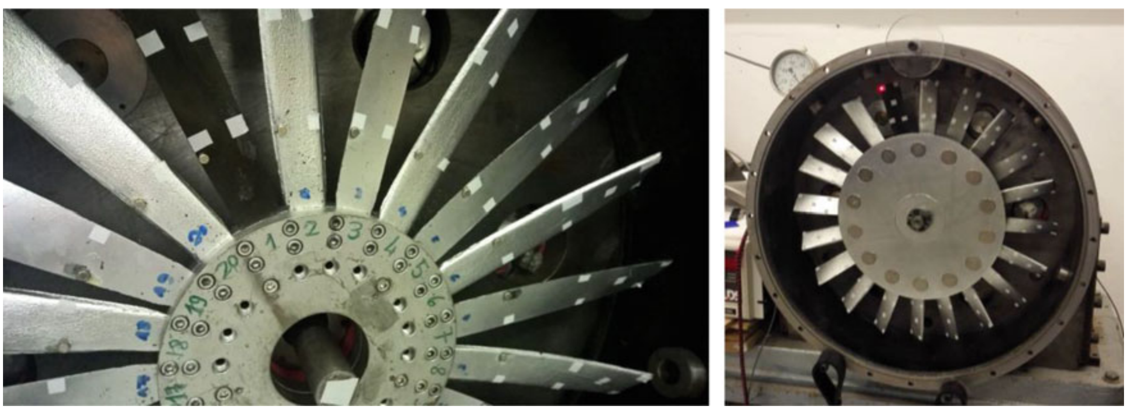

Fig. 4.20 Bladed disc on the left and exciter on the right

was not used). The 14-DC magnetic exciter was spun between 120 and 1500 rev/min with a speed increment of 0.1 rev/min. A total of 80 measurements were carried out. Figure 4.21a shows the vibration response of one measurement point, where the red arrow shows the aliased responses measured because of multiple engine orders excitations. Figure 4.21b shows a zoom around 130 Hz of the resonances of the first bending mode. This was not a surprise after the tests carried out by modal hammer and showed in Fig. 4.4c. The vibration of the aluminium disc was also monitored to check if any vibration mode would be excited as result of exchanges of forces between the magnets. Fortunately, this was not the case for the response under study.

The excitation method showed great flexibility and safe use. In fact, the mechanism is simpler than what is required by a series of amplifiers and controllers used for operating AC magnets. The level of forces generated are also higher than what can be achieved by AC systems. There could be some unknowns, but not investigate here, about the shear forces caused by spinning DC magnets. In practice, a bladed disc is immersed inside a fluid of combusted gasses, and it is not unreasonable to think a combination of normal and tangential forces acting on the spinning blades. In the presented test case, the rich magnetic environment spins around the blades causing a similar combination of tangential and normal forces. It is clear that the centrifugal load effect cannot be considered in this type of experiments but, nonetheless, these effects can be replicated by mirroring the proposed test configuration; the magnets are fixed, and the bladed disc rotates.

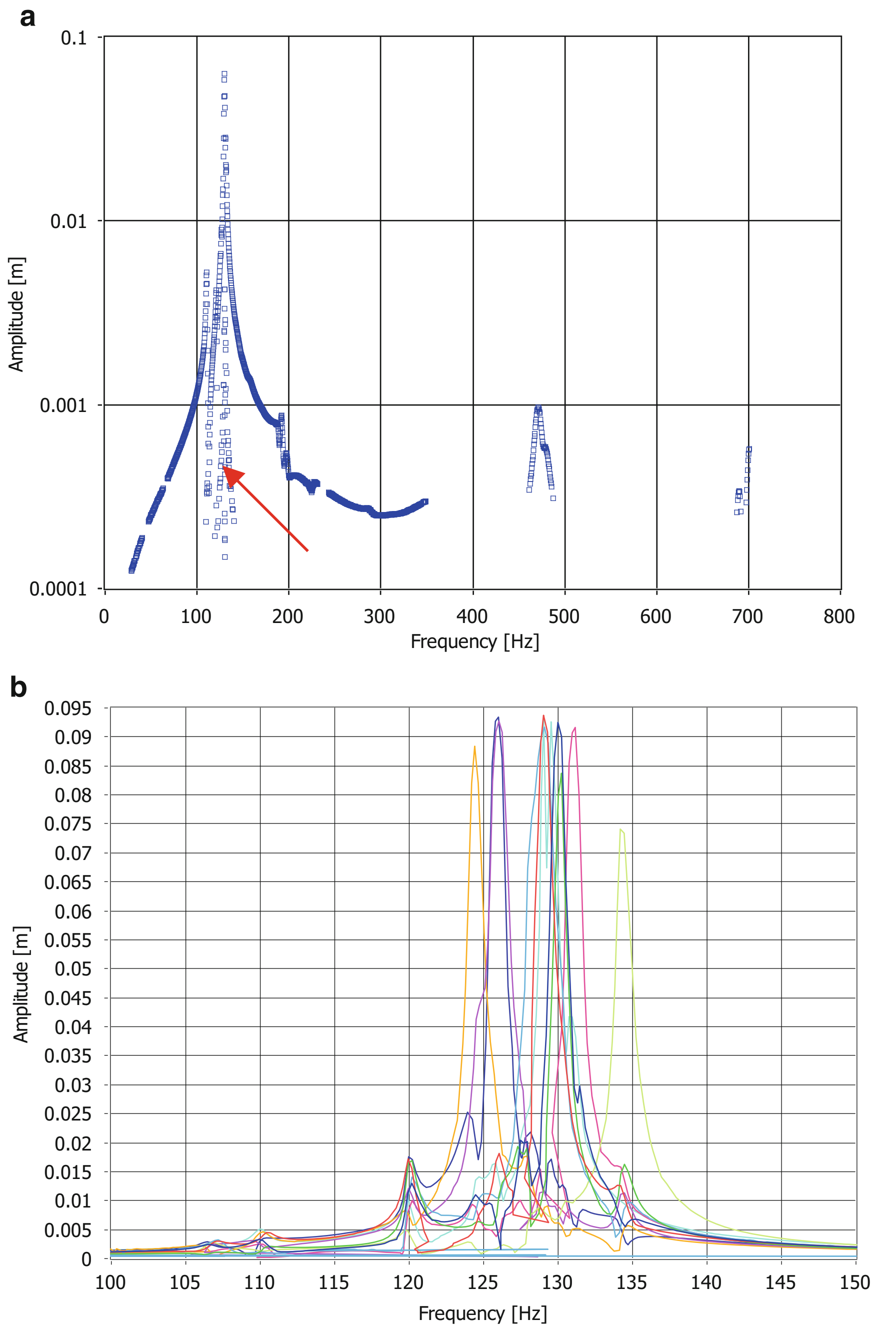

Fig. 4.21 Vibration response of one point in (**a**) and multiple points in (**b**)

4.6 Conclusions

This research paper presented the challenges of exciting a composite bladed disc. The major complication was caused by little transmissibility which required to excite the blades individually. Modal impact and the DC electromagnetic exciters testing showed a great frequency scatter for modes around 130 Hz. The use of a 3D single point LDV was very helpful to visualize the 3D motion of the measurement points but the test execution was very time consuming. The DC EM exciter showed some interesting potential but at present the excitation system also showed several drawbacks. The last excitation system was achieved by using 14 DC magnets installed on an aluminium disc. The disc could be rotated to generate a travelling wave excitation. The design of such a system was anticipated by a set of simulations to select the best target magnet to install on the blades. Experiments on force characterisation were performed, and these yielded to encouraging results, but also to the revelation of a harmonic at 7 kHz not yet understood. The excitation forces generated were considerably high. The final phase of the tests was to perform forced response measurements on all the 20 composite blades. The results showed a clear scatter of the first bending mode resonances which, again, was expected following the modal hammer test.

In conclusion, the 14-DC magnetic exciter showed good ability to provide strong excitation forces. The measurement system is very simple. The measurements are also simple to carry out because of the stationarity of the bladed disc. The large forces exerted by this exciter can open several avenues into new studies of blade root contact conditions, which are amplitude dependents.

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